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Evaluation of Slot Allocation Strategies for TDMA Protocols in Packet Radio Networks
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This paper examine the delay performance of packet radio networks using a time division multiple access (TDMA) channel access protocol. Two different methodologies for assigning time slots to nodes are considered – Node and Link allocation. The performance of each strategy is evaluated using a detailed radio network simulation. In addition to the delay for single destination packets, two broadcast protocols are used – multidestination routing and flooding. In all cases it was found that Node allocation provides better delay performance than Link allocation.

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Evaluation of Slot Allocation Strategies
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David S. Stevens and *Mostafa H. Ammar*

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Abstract

Time Division Multiple Access (TDMA) protocols provide packet radio networks with two features that facilitate efficient communications. First, they eliminate the possibility of collisions. Second they allow for the spatial reuse of the radio channel bandwidth by permitting more than one node to transmit at once. Many different algorithms have been proposed to maximize the reuse of the bandwidth and simultaneously minimize the transmission cycle length. The resulting slot assignments of these algorithms can be grouped into two general strategies for assigning transmissions rights to nodes - *Node* and *Link Allocation*. Node allocation involves assigning a node a timeslot during which it may transmit to any of its neighbors. A link allocation strategy allocates unique timeslots to a node for each directed link it has to a neighbor. A node can transmit to a neighbor only during the timeslot assigned to the directed link for that neighbor. Each allocation strategy has its advantages and disadvantages. Yet, it is not clear which will provide better delay performance when employed in a packet radio network.

In this paper the performance of each allocation strategy is evaluated using a detailed simulation. First, the traffic delay experienced at a single node is examined when the two allocation schemes are employed. Next, the two strategies are evaluated in a simulated packet radio network. For dynamic networks, a methodology commonly used to assign initial timeslots in both node and link allocation schemes is implemented. This procedure involves traversing the network and using a greedy selection algorithm to assign collision free timeslots to either nodes or directed links. After slot assignments are made, the average end-to-end delay experienced by single destination messages is measured. Finally, broadcast messages are introduced into the network. Broadcasting in a packet radio network using a TDMA channel access protocol introduces additional issues that are addressed. Two different broadcast protocols used in the simulation - multidestination routing and controlled flooding. Average delay times for both single destination and broadcast messages are measured for each broadcast protocol.

When only single destination messages are traversing the network, a node allocation strategy results in lower average delay times. In a mixed traffic environment consisting of both single destination and broadcast messages (irrespective of the broadcast protocol in use), the node

allocation scheme again offers better performance than the link allocation scheme. The results are explained by the longer transmission cycles required by the link allocation strategy to insure a collision free environment. These findings are significant because they imply that if a TDMA channel access protocol is to be used in a dynamic packet radio network, better performance will be obtained if a node allocation strategy is adopted.

1 Introduction

A Packet radio network (PRNET) offers two unique features that a cable connected store-and-forward network lacks - a broadcast medium and a dynamic topology. The broadcast medium permits any network node within range of the transmitting node to receive the packet. The use of a radio channel instead of wires to link the network nodes also permits them to move about freely. Yet these same features are the source of the major challenges to efficient protocol design. The broadcast medium limits the number of nodes that can successfully transmit at the same time while mobile nodes can create problems for higher level routing protocols. The nature of the broadcast medium causes the functions between layers to be highly *interdependent*[1]. Therefore the implementation of the low level channel access protocol can have a great effect on the performance of other higher level protocols such as broadcasting.

There are two general approaches for medium access control in the radio environment [2] - random access and deterministic scheduling schemes. Random access schemes such as ALOHA or Carrier Sense Multiple Access (CSMA) are algorithmically simple but do not guarantee a "quality of service". On the other hand, algorithms that establish a deterministic transmission schedule like those used for a Time Division Multiple Access (TDMA) scheme, make a considerable effort at maximizing the spatial reuse of the available bandwidth while simultaneously eliminating the possibility of collisions. This facilitates the delivery of packets throughout the network.

TDMA protocols can be grouped together by how they divide the channel bandwidth among the network members. Two common schemes are used and we refer to these two techniques as *node* allocation and *link* allocation. For static networks different allocation algorithms have been proposed to minimize the transmission cycle length while maximizing the spatial reuse of the bandwidth [3, 4, 5, 6]. These are centralized slot assignment algorithms that require global knowledge of the network topology. A distributed node allocation algorithm has been proposed in [2] for dynamic networks and a link allocation algorithm has been presented in [7]. Both algorithms use greedy selection heuristics to create an initial collision free environment while maximizing the spatial reuse of the broadcast channel.

Although packet radio network protocols are designed to carry primarily single destination packets, point-to-multipoint communication is required for many applications. Re-

cently, the issues involving the delivery of packets addressed to multiple destinations in a packet radio network have received attention, with the emphasis being on broadcasting [7, 8, 9, 10, 11]. Many of these protocols for broadcasting require the use of a TDMA channel access scheme. Yet, the performance of broadcast communication in packet radio networks using a TDMA channel access protocol has not been investigated. We consider networks carrying single destination packets as well as broadcast packets.

For a packet radio network using a TDMA channel access scheme, it is not clear which time slot allocation strategy - node or link, will provide the better delay performance. In this paper we examine the delay experienced by single destination and broadcast packets in networks using link and node allocation strategies. As mathematical analysis of arbitrary topologies is not feasible , we conduct our investigation using a detailed simulation. In addition to determining which time slot allocation strategy provides better delay, our investigation led us to develop insights into the implications of adopting either a link or slot allocation strategy.

In the section that follows we describe our version of the link and node allocation schemes and discuss their attributes. Section 3 describes our simulation model. In Section 4 we discuss the results obtained using our simulation for networks carrying only single destination packets and present an analysis of delay under light load conditions. In Section 5 we discuss the delay performance of two protocols: multidestination routing and controlled flooding, that can be used to route broadcast packets in packet radio networks using TDMA. Section 6 contains some concluding remarks.

2   Node and Link Allocation Strategies

In this section we discuss the node and link slot allocation schemes and describe our algorithm for each. We then examine the implications of the transmission cycle length and discuss the advantages and disadvantages of each allocation method.

2.1   Description

Both node and link allocation methodologies solve the basic problem of assigning transmission rights to nodes so that collisions will not occur and spatial reuse of the channel is

achieved.

For node allocation schemes, each node is assigned a single time slot in each transmission cycle during which it can transmit to *any* of its neighbors. A link allocation strategy allocates unique time slots in the transmission cycle to a node for each directed link that it has to a neighbor. (Note that a link between nodes u and v constitutes two directed links in this scheme. One goes from node u to v and the other goes from v to u.) A node can transmit to a neighbor only during the time slot assigned to the directed link for that neighbor. Figure 1 illustrates how slots would be allocated for each method. The numbers represent the time slot during which a node can transmit.

A common methodology for allocating time slots in a packet radio network involves traversing the network in some manner and using a greedy selection algorithm to assign time slots to nodes or directed links. A time slot is available if assigning it does not result in a collision. To eliminate collisions the following two conditions must hold:

C1. Node u does not transmit in the same period during which a neighbor is transmitting to it. (A node cannot send and receive simultaneously.)

C2. Only one neighbor of node u can transmit to it during any one period of time. (A node cannot simultaneously receive two transmissions.)

The assignment algorithms we use are modeled after the link allocation algorithm described in [7]. The shortest transmission cycle length possible is used in our simulation.
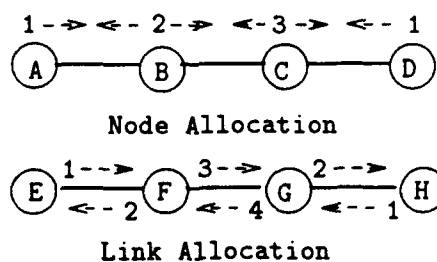

Figure 1: Link and Node Slot Assignments

This length is equivalent to the highest slot number assigned to any node.

In making the slot assignments for node allocation (see Figure 2), we begin by selecting any node v_i in the network and mark it as selected. All v_i's unmarked neighbors are marked as selected and placed in an assignment queue. (In this first step all v_i's neighbors will be unmarked). Using a greedy selection process, node v_i is assigned the first available time slot that does not violate conditions C1 and C2. The next node, v_j, in the queue is selected and assigned a slot. All of v_j's neighbors that are not already marked as selected, are marked and placed in the queue. In determining v_j's transmission slot we eliminate all time slots during which its neighbors are transmitting and any slots during which its neighbors are receiving. In v_j's case only one slot has been allocated for transmitting, that of v_i. Thus v_j is assigned the next slot and the data structures are then updated. This process continues with the removal of the next node from the queue. The algorithm terminates when all nodes have been assigned a time slot.

A few changes to the algorithm are necessary for the link allocation. A time slot is assigned to each of node v_i's directed links to a neighbor. If the slot chosen is an odd numbered slot, the next slot is assigned to the receiving link from that neighbor. If it is an even number, the prior slot number is used. Thus each link is allocated a pair of slots 1-2, 3-4, etc. When determining which slots are not available for node v_i to use to transmit to v_j, we still eliminate any slots that any of v_i's neighbors are using for the reception of packets from their neighbors. However not every transmission slot used by v_i's neighbors needs to be eliminated from consideration as a possible slot for v_i's use. Only those slots used by v_i's neighbors to transmit to v_i and those used by v_j to transmit are eliminated. A transmission slot used by v_i's neighbor v_k to transmit to a distant node v_l can be reused by v_i.

2.2 Cycle Length Upper Bounds

We let l_i represent the number of *hearing* links that a node i has and we let $l_{max} = \max_i l_i$. Note that in a static network l_i and l_{max} are constant over time, if the link quality does not change. In a very dense network, it is possible that a node has more hearing links than the radio is physically capable of handling. Though radios cannot communicate over these links, slots would have to be allocated for them to avoid collisions.

```
Data Structures:
  Transmission Slots of the Network Nodes
  Receiving Slots of the Network Nodes
  Receiving Slots of each Node's Neighbors

BEGIN
    select any node and mark it as selected;
    add this node to a queue;
    WHILE the queue is NOT empty
       current_node = 1st in queue;
       mark   any of current_node's neighbors that are not
              already marked and add them to the queue;
       assign the first available time slot to the current
              node that does not violate:
         C1:  the time slot assigned is not the same as one
              used by its neighbors for transmitting
         C2:  the time slot assigned is not the same as one
              during which one of its neighbors is already
              receiving;
       update the current_node's neighbors to indicate they
              are now receiving in the newly assigned
              time slot;
    END WHILE;
END BEGIN;
```

Figure 2: Node Allocation Algorithm

For both schemes, when l_{max} is known, we can compute an upper bound, TC_{ub}, for the number of slots that could be required in a transmission cycle (see [2] and [7]):

$$\text{node } TC_{ub} = min\{|N|, l_{max}^2 + 1\} \qquad (1)$$

$$\text{link } TC_{ub} = min\{|N| * l_{max}/2, \; 2(l_{max}^2) - 2l_{max} + 1\}. \qquad (2)$$

In many networks both allocation schemes may result in a transmission cycle length smaller than the upper bound.

We consider TDMA strategies that allocate one slot per node per cycle in the node allocation scheme and one slot per directed link per cycle in the link allocation scheme. Thus a longer transmission cycle increases the potential for greater delay times in the delivery of packets throughout the network.

2.3 Comparison

Each technique has its advantages and disadvantages. The link method allows two neighboring nodes to transmit simultaneously whenever the destination nodes are not neighbors of both transmitting nodes. In Figure 1 both node F and G can transmit during time slot 2 without collisions occurring. In addition, every node can send a single packet to each of its neighbors during every transmission cycle. The disadvantages are that for a given network with more than two nodes, the transmission cycle length may be longer than that required for node allocation techniques (see Section 4). Furthermore, a higher level broadcast protocol cannot take advantage of the broadcast medium. Instead, broadcast packets must be routed as separate packets to each neighbor. Again referring to Figure 1, if node F needs to broadcast a packet , it must send the packet twice. During time slot 2 it transmits the packet to node E and then during time slot 3 it transmits the same packet again to node G. In a sense, the link allocation scheme attempts to simulate a wire based network so that all higher level protocols may be used without modification.

The advantages and disadvantages of a node allocation scheme are the converse of the link allocation. On the plus side, the transmission cycles are shorter thereby reducing the potential for longer delays. Second, some multidestination protocols can take advantage of the radio channel, which permits a single transmitted packet to be received by all neighbors. Node B needs only to transmit a broadcast packet once during time slot 2 and it will be received by both nodes A and C. The disadvantages are that if a node v has l neighbors, l transmission cycles are required to transmit distinct single destination packet to each. In Figure 1, two transmission cycles are necessary in order for node B to transmit to each of its two neighbors. Finally, two neighbors cannot transmit simultaneously even if their packets will not collide at their intended destinations. Node B cannot transmit a packet to node A while node C transmits a packet to node D even though a collision would not result at either node A nor D.

3 Simulation Description

3.1 Network Protocols

The following is a description of the protocols used in our simulation. One may have to adopt different acknowledgment and switching approaches depending on the allocation scheme used as discussed below.

Packets arriving from external sources are routed over a minimum hop path. These routes are discovered in a distributed fashion as prescribed by DARPA's current PRNET algorithms [12]. To limit congestion and impose some flow control, we also followed the general ideas set forth in DARPA's current pacing protocol [13]. This is accomplished by setting a timer equal to three transmission cycles. If an acknowledgement is not received before the timer elapses, the node retransmits the packet. Since failure to receive an acknowledgment is usually due to congestion rather than errors (no collisions and forward error correcting code), the timer is set to six transmission cycles for the second transmission. Should an acknowledgement again not be received prior to the lapse of the timer, the final retransmission has the timer set to nine cycles. If the packet remains unacknowledged, it is discarded and the next one transmitted. The retransmission of discarded packets is assumed to be part of the external packet arrival process.

Our simulation employs DARPA's stop-and-wait philosophy that permits only a single packet to be outstanding to each neighbor. Thus a node cannot transmit a second packet to a neighbor until it first receives an acknowledgment for the previous packet that it sent to that neighbor. Note that this does not prevent the node from transmitting to its other neighbors nor from receiving packets.

In a node allocation strategy passive acknowledgments are possible. (A passive acknowledgment is when the reception of the packet being forwarded by a neighbor suffices for an acknowledgment.) This is feasible because each node can receive the transmissions of its neighbor without suffering a collision and thus it would hear its packet being forwarded. Therefore, separate active acknowledgments are generally only sent when a packet reaches its final destination or when the passive acknowledgment was sent but not received. A link allocation strategy requires that an active acknowledgment be sent for each packet. A collision will normally prevent a node from correctly receiving the forwarded packet. This

is because the slot assigned to the directed link over which the packet is being forwarded by the neighbor is distinct from the one during which the neighbor uses to communicate with the originating node. However, these acknowledgments are piggybacked with other data packets whenever possible.

First-come, first-serve (FCFS) queues are used by each node for determining which packet should be transmitted next. A packet can normally only be forwarded if the current cycle time slot is equal to the node's transmission time slot and the packet is at the head of the transmission queue for the next node. For the link allocation scheme separate queues are maintained for each neighbor. However, for node allocation only one queue is needed as there is only a single transmission slot per node per cycle which is used to transmit packets to all neighbors. If a strict queue discipline was maintained, the stop-and-wait policy would result in wasted bandwidth. Suppose two packets destined for the same neighbor are in the first two positions of a queue and a third packet destined to a different neighbor is in the third. During the node's transmission slot it would forward the first packet. If it has not received an acknowledgement by the time of its transmission slot in the following transmission cycle, the slot would be wasted. Therefore, when the first packet in the queue cannot be transmitted because the node is waiting for an acknowledgment, the queue is searched for an available packet that can be transmitted to another neighbor.

3.2 Random Networks

We are interested in reaching conclusions about the use of the two slot allocation strategies in general. It is not sufficient to simulate one particular network as our conclusions may be affected strongly by the network topology. Also we found that end-to-end packet delays depend strongly on the network's density. Therefore, in our evaluation we constructed three different types of networks with varying degrees of connectivity: a *sparse* network, a *medium* density network and a *dense* network. We set the maximum number of neighbors for a node in these networks to be 3, 5 and 8 respectively. For each type of network we randomly generated six networks. Our delay results are reported as averages across the six networks. Figure 3 shows a sample of a randomly generated sparse network. In this figure the number above a node indicates the resulting transmission slot for the node using our node allocation algorithm. Figure 4 shows the same network, however, the transmission slots displayed next to a node are those obtained by using our link allocation algorithm.

3.3 Other Assumptions

In addition to the above we make the following assumption in our simulation.

- Packet radio networks usually employ some form of forward error correcting code [12, 14]. In addition after the error correcting procedures have been completed, some time will be required to prepare the packet header for transmission. Thus in our treatment of the problem we assume that a node receiving a packet during a time slot cannot immediately forward the same packet during the following time slot. This assumption will only affect the delay on some routes and then only at low load levels as queues will form at higher levels.

- All packets are of equal length. The slot duration represents packet transmission time plus the the maximum node to neighbor propagation delay. (A typical slot duration is on the order of a small fraction of a millisecond [15].) We use the slot duration as our time unit.

- The external packet arrival process into the network is modeled as a Poisson process. The arrival rate is varied to obtain different traffic loads.

- An arrival is equally likely to arrive at any given node. For single destination packets the destination node is equally likely to be any other node in the network.

- The probability that a packet or acknowledgment is delivered in error is p. Packets in error are ignored.

4 Networks with Single Destination Packets

In this section we first present our simulation results and then present an analysis of packet delay at light loads.

4.1 Simulation Results

In an actual network many factors affect the delay. These include the transmission cycle length, the network topology, routing, acknowledgments, and transmission errors. Still one would expect that if all factors are equal including TDMA cycle length, link allocation

Network	6 Networks		Upper Bound	
Type	*Node*	*Link*	*Node*	*Link*
Sparse	4.66	8.66	10.00	13.00
Medium	7.00	16.33	26.00	41.00
Dense	11.00	35.00	65.00	113.00

Table 1: Average Transmission Cycle Lengths - 30 Nodes

will provide better delay performance for single destination packets. This is because a node using link allocation can transmit single destination packets to each of its neighbors in one transmission cycle. However, the slot assignment algorithms do not result in the identical transmission cycle lengths. In fact as l_{max} increases (i.e., the density of the network increases), the cycle length for link allocation becomes larger than that required by node allocation for the same network. This is illustrated in Table 1 where the average cycle lengths obtained for the six randomly generated networks are shown for the three network densities considered. The upper bound [1] in equations (1) and (2) are also shown in the table for networks with a large N. Thus there is a trade off in the two strategies between the cycle length and the number of neighbors during a cycle to which a node can transmit single destination packets.

We use our simulation to evaluate the delay performance of single destination packets in packet radio networks employing both link and node slot assignment schemes. The time required to deliver a single destination packet is the interval from when the packet initially arrives in the system until its final reception at the destination node. We measure these durations after steady state is reached. We considered two cases, one with $p = 0$ and the other with $p = 0.01$.

A graph comparing the average delays across the six randomly generated networks with no transmission errors is shown in Figure 5. Figure 6 shows the results when p, the probability of packet error, is 0.01. In all cases, node allocation offers better performance than link allocation. Thus it appears that the shorter cycle length of the node allocation

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[1] This bound is not approached in our simulation because our network generator attempts to generate realistic dispersed networks with the number of links per node varying over the entire possible range. Networks with a high degree of connectivity would require a transmission cycle length closer to the upper bound.

scheme, more than compensates for the additional transmissions slots per cycle that are available to each node in the link allocation scheme.

In addition to the cycle length/number of transmissions per cycle tradeoff, the plots shown in Figures 5 and 6 demonstrate the resolution of another interesting tradeoff: cycle length/path length. Except at very high load levels, the performance of the node allocation policy varies only slightly as the density of the network changes. One would expect longer system times for packets traversing a sparse network than in a dense network with the same number of nodes. This expectation is based on the fact that in a sparse network a packet must traverse more hops to reach its destination. However in a dense network, although the distances are shorter, the resulting transmission cycle length is greater. Thus packets are delayed longer at each node before being forwarded. For node allocation the shorter cycle length generated in sparse networks usually compensates for the longer distances the packets must travel. In more dense networks the shorter distances offset the increase in delay experienced by packets due to the longer transmission cycle. For link allocation this trend does not appear to hold. As the network density increases, there is an increase in the average system time. The increases become more severe at higher load levels and even more so in the presence of errors.

Errors in general increase average delay times for both node and link allocation. Errors affect the delay more adversely in sparse networks because the longer routes mean a higher probability of a packet experiencing an error. In addition link allocation is also more affected by errors than node allocation. This is because timeouts and retransmissions are a function of the cycle length. Thus when an error does occur, a packet spends more time waiting to be retransmitted when link allocation is used than when node allocation is used with its shorter transmission cycle length.

Our results indicate that in actual networks a node allocation policy is more appropriate because it requires a shorter transmission cycle. The shorter cycle produces better delay performance.

4.2 End-to-End Delay at Light Load

In this section we derive an expression for the expected end-to-end delay for single destination packets in packet radio networks using node and link allocation. A packet's end-to-end

delay is defined as the time from when it first arrives until it is fully received by its ultimate destination. Let $D_{i,j}$ be the expected end-to-end delay for packets originating at node i and destined for node j. The overall expected end-to-end delay in the network, D is given by

$$D = \sum_{i=1}^{N} \sum_{j=1;j\neq i}^{N} \frac{\gamma_{i,j}}{\gamma} D_{i,j} \tag{3}$$

where $\gamma_{i,j}$ is the arrival rate of packets at node i with destination node j and $\gamma = \sum_i \sum_{j,j\neq i} \gamma_{i,j}$.

The delay experienced by a packet is the sum of its delay at the source node before its initial transmission and the forwarding delays at all intermediate nodes. If L is the TDMA cycle length then a packet will on average wait for $\frac{L}{2} + 1$ time units (slot duration is our time unit) until it initially is fully transmitted. (Recall we only deal with the light load situation and we can thus assume negligible queuing delays.) We let $\pi_{i,j} = (i, n_1, n_2, \ldots, j)$ be the path followed by packets from i to j. We thus have

$$D_{i,j} = (\frac{L}{2} + 1) + f(\pi_{i,j}) \tag{4}$$

where $f(\pi_{i,j})$ will depend on the slot allocation method in use.

For *node* allocation, we let $d(n_1, n_2)$ represent the time from when a packet is fully received by n_2 (from n_1) until it is fully transmitted (i.e., forwarded). Thus in a network using node allocation we have

$$f(\pi i, j) = \sum_{\substack{(n_1, n_2) \in \pi_{i,j} \\ n_2 \neq j}} d(n_1, n_2). \tag{5}$$

Under the assumption of light load (i.e., no queuing delay) and recalling that a node cannot forward a packet in the slot immediately following the packet's reception we have

$$d(n_1, n_2) = \begin{cases} (\mathcal{S}(n_2) - \mathcal{S}(n_1)) \bmod L & if\ (\mathcal{S}(n_2) - \mathcal{S}(n_1)) \bmod L \neq 1; \\ L+1 & if\ (\mathcal{S}(n_2) - \mathcal{S}(n_1)) \bmod L = 1; \end{cases} \tag{6}$$

Type	Node		Link	
Network	Computed	Simulation	Computed	Simulation
Sparse	19.76	19.68	28.95	29.11
Medium	17.22	17.03	34.08	34.70
Dense	18.07	18.21	50.58	51.71

Table 2: Light Load Delay

where $S(x)$ is the slot assigned to node x under the node allocation strategy and the slots are numbered $0, 1, \ldots, L - 1$. The light load expected end-to-end delay for packet radio networks using node allocation can thus be computed using equations (3) through (6).

For networks using the link allocation strategy we let $d(n_1, n_2, n_3)$ be the delay from when a packet is fully received by n_2 (from n_1) until it is fully transmitted to n_3. Thus for link allocation we have

$$f(\pi_{i,j}) = \sum_{(n_1, n_2, n_3) \in \pi_{i,j}} d(n_1, n_2, n_3) \tag{7}$$

Under the same assumptions used for equation (6) we can write

$$d(n_1, n_2, n_3) =$$

$$\begin{cases} (S(n_2 \rightarrow n_3) - S(n_1 \rightarrow n_2)) \bmod L & if \ (S(n_2 \rightarrow n_3) - S(n_1 \rightarrow n_2)) \bmod L \neq 1; \\ L + 1 & if \ (S(n_2 \rightarrow n_3) - S(n_1 \rightarrow n_2)) \bmod L = 1; \end{cases} \tag{8}$$

where $S(x \rightarrow y)$ is the slot assigned for the link $x \rightarrow y$ and slots are numbered $0, 1, \ldots, L - 1$.

In Table 2, we show the expected light load end-to-end delays computed using the above equations. We use the same parameters as in the simulation i.e., $\gamma_{i,j} = 1/(N(N - 1))$ and the delays are averaged across six randomly generated networks. The simulation results are obtained using a total arrival rate $\gamma = 0.01$.
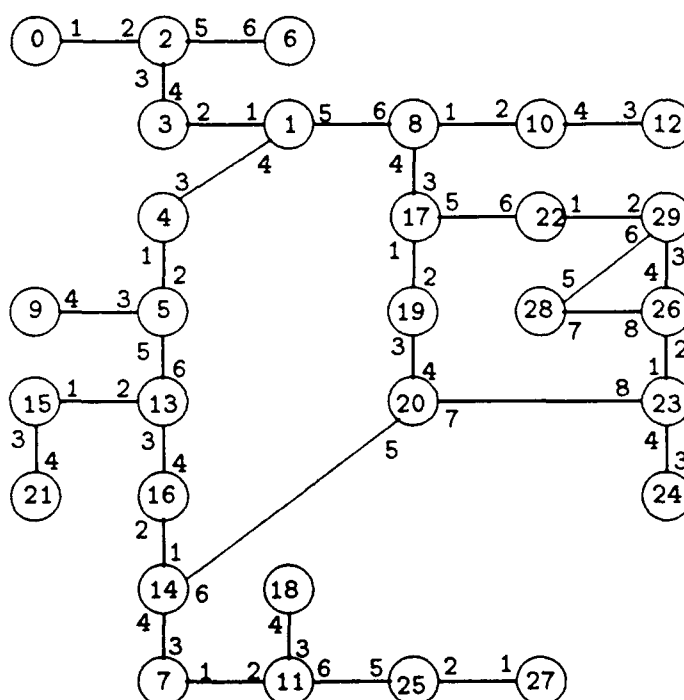
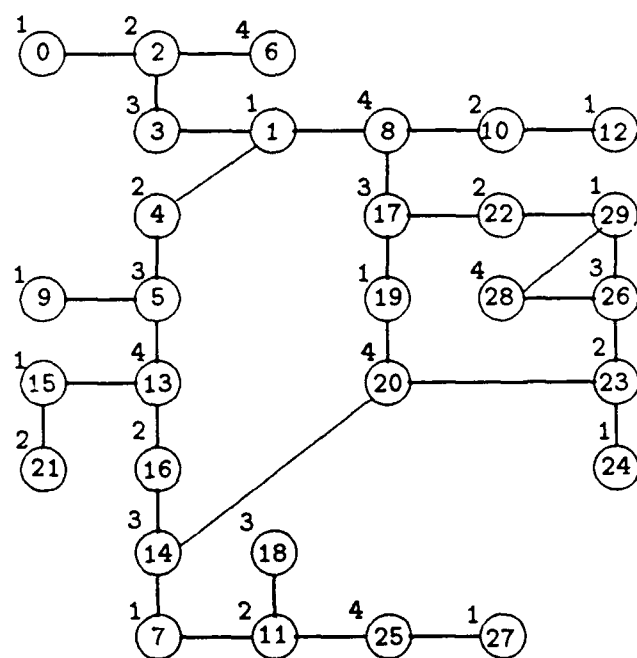Figure 3: Sample Sparse Network NODE Allocation (Cycle Length = 4)

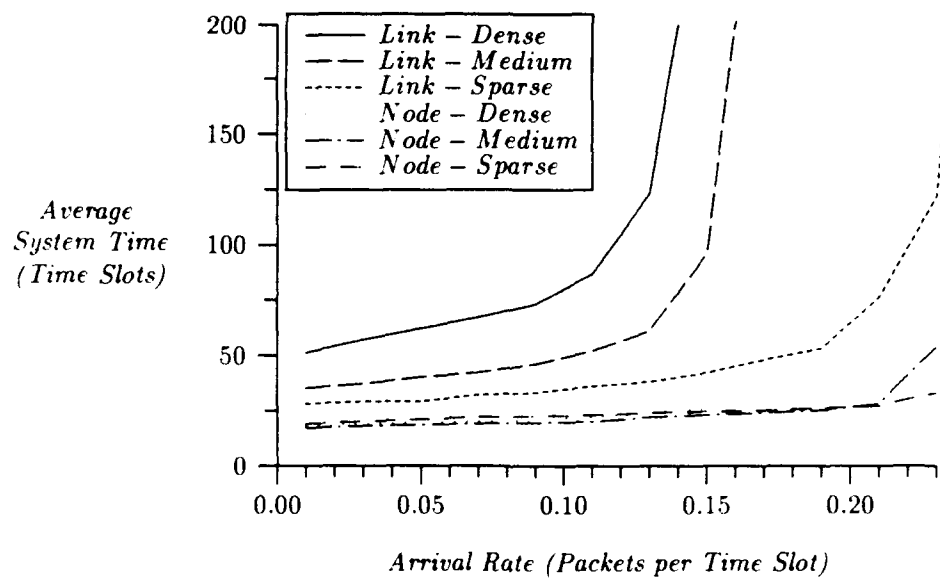Figure 4: Sample Sparse Network LINK Allocation (Cycle Length = 8)

15

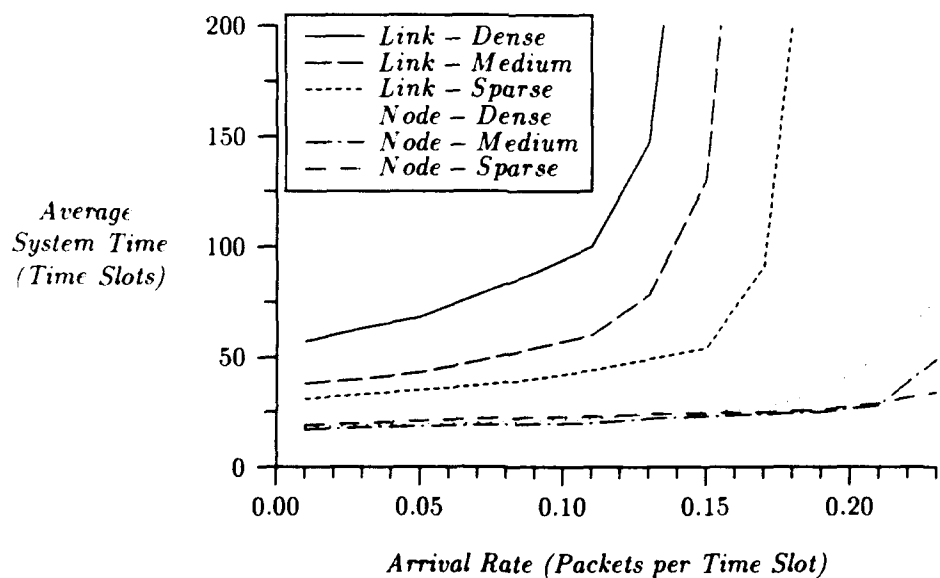Figure 5: Single Destination Packets, No Transmission Errors

Figure 6: Single Destination Packets, With Transmission Errors

5   Networks with Broadcast and Single Destination Packets

In this section we investigate the delay performance of two broadcast protocols - multidestination routing and controlled flooding, in conjunction with both TDMA channel access schemes. These broadcast protocols (which were adapted from ones used in wire-based networks [16]) are described next. This is followed by a discussion of the delay results from our simulation with mixed broadcast and single destination traffic. Our simulation model is basically the same one described in Section 3 with the modifications described below. As in Section 4, our conclusion is that for both broadcast protocols, a node allocation TDMA strategy offers better delay performance.

5.1   Multidestination Routing

In a multidestination routing protocol (see [16]) a node receiving a packet determines the minimum hop path for each destination contained in the header. (Packet headers may contain multiple destination addresses.) The node then creates multiple copies of the packet, one for each link over which it must forward the packet. The header in each of these packets contains only those destinations that have a common next node.

Implementing multidestination routing for broadcast packets requires only minor changes to the protocols used for single destination packets. The major adjustment being a node receiving a broadcast packet might have to create more than one packet to forward. This has the effect of increasing the actual load level and results in increased delay times. No changes are required for determining routes, maintaining queues or handling acknowledgments. This is true for both the link and node allocation schemes.

Implementing multidestination routing in a network using a node allocation scheme fails to take advantage of the broadcast capability of the medium. This is because a node may transmit packets with the same data but with different headers several times, one to each neighbor. In a node allocation scheme a single transmission is guaranteed to arrive at all of a node's neighbors with no collisions. Thus one can improve on the multidestination routing protocol by transmitting one copy of the packet to all neighbors. The header of such a packet must contain the set of neighbors that should receive the packet. For each neighbor in the header, a list of destinations is also provided. This scheme will clearly

reduce the delay for broadcast packets because only one cycle is now required to forward such a packet. However implementing this modified scheme for broadcasting will create difficulties with the stop-and-wait protocol. These are examined in the following section describing controlled flooding. To compare the two TDMA channel access schemes, our simulation does not implement the improved version of multidestination routing. Thus our delay results for packet radio networks using node allocation TDMA and the unmodified multidestination routing algorithm are somewhat pessimistic.

5.2 Controlled Flooding

In this protocol [16] a broadcast packet is forwarded to all neighbors (other than the one from which the packet is received) if the packet has not been previously forwarded. If the node has already seen the packet, it is ignored. Node allocation requires only one transmission to deliver the packet to each neighbor. Implementing controlled flooding using a link allocation scheme still stipulates that separate packets be transmitted to each neighbor. It also requires more transmissions than would be necessary for the multidestination routing protocol where a packet is typically only forwarded to a subset of the neighbors, not all.

Using controlled flooding for broadcasting in a network employing node allocation poses complications to the stop-and-wait protocol. Assume that node v has three neighbors - u_1, u_2, and u_3. (Recall that in the node allocation scheme only one queue is used to store packets awaiting transmission.) Suppose two broadcast packets originating at node v are queued for transmission. It transmits the first broadcast packet in a single slot that is received by its three neighbors. Assume that, before node v's next transmission slot, two events occur - u_1 acknowledges the first broadcast packet and a single destination packet also originating at v destined to u_1 is queued behind the second broadcast packet. Transmitting the second broadcast packet in its next transmission slot would violate the stop-and-wait policy at nodes u_2 and u_3. Node v could search the queue for the single destination packet to u_1 and transmit it to prevent the slot from going unused. Yet, if during the following cycle nodes u_2 and u_3 acknowledge the first broadcast packet and node u_1 fails to acknowledge the single destination packet, node v again cannot transmit the second broadcast packet because of the outstanding single destination packet to u_1. In periods of heavy load this packet may never get transmitted. Maintaining a strict queue discipline would insure all packets will be delivered but at the expense of wasted bandwidth and increased average

delay times. Expanding the window size will increase the probability that a broadcast packet is transmitted, but it does not guarantee it, especially in periods of heavy load and at nodes with many neighbors. It also would require more buffers that are usually not available in packet radios.

Our solution to this problem is to maintain two separate queues for node allocation, one for broadcast packets and one for single destination packets. Only one of each type packet may be unacknowledged. Single destination packets are serviced as before. Broadcast packets are handled differently. Before a broadcast packet can be transmitted, all neighbors must have acknowledged the previous one. Since two queues are maintained and there is only one transmission slot available, we alternate the service priority between the two. Timeouts and retransmissions are handled as before with one exception. The header of the retransmitted broadcast packet contains only those neighbors that have not yet responded with an acknowledgment.

Using controlled flooding in a link allocation scheme does not create a similar problem. Separate copies of the broadcast packet can be placed in the queue of each destination neighbor. Like multidestination routing, both broadcast and single destination packets can be serviced together in a FCFS queue. However, to make a fair comparison of the two TDMA allocation schemes we implement link allocation using two separate queues, one for single destination packets and one for broadcast packets, and allow one outstanding transmission per queue.

5.3   Simulation Results

The delay for broadcast packets is measured from the time a packet arrives in the network until *all* nodes receive it. As with single destination packets, we ran the simulation with an error probability of $p = 0$ and $p = 0.01$. Errors had a similar effect on the average delay times as those observed with single destination packets. (See Figures 5 and 6). They did however affect multidestination routing more than flooding. This was because of the two different queues used for each type packet in the flooding protocol. In this protocol a broadcast packet is not delayed in the queue because of an error to a single destination packet and a single destination packet is not delayed because of an error to a broadcast packet. In multidestination routing both packet types are queued together in single queues.

Thus an error to either type packet increases delay times of all packets in the queue. The results shown in this section are those with $p = 0.01$.

We initially let 10% and then 20% of the packets arriving in the system be designated as broadcast packets. The results of these two cases are similar with the 10% case producing lower average delay times due to fewer broadcast packets. The one exception being the average delay times for broadcast packets using controlled flooding at low load levels. Here the difference between the delay times for broadcast packets at the 10% and 20% rate of arrival is negligible. This was because of the alternating service priority between the two queues used in this protocol, which in effect creates a priority scheme for broadcast packets. Since there are fewer broadcast packets in the network at low traffic levels, queues will not normally develop for this type packet. Thus they are serviced almost immediately. This expedites their delivery and results in little difference in their delay. The graphs presented in this section are those for when the number of broadcast packets is equal to 20% of the system arrivals.

The average system times for mixed traffic of both broadcast and single destination packets in a sparse network using multidestination routing are shown in Figure 7. Figure 8 shows the results for the same networks using a controlled flooding protocol. As should be expected, single destination packets experience much lower average delay times than broadcast packets. In both protocols, node allocation offers lower average delay times.

Figures 9 and 10 compare the delay times between multidestination routing and controlled flooding in a medium density network. Figure 9 displays the results for just broadcast packets while Figure 10 shows the results for single destination packets. Again we observe that for both protocols, node allocation offers better performance than link allocation with controlled flooding performing better than multidestination routing. Note that as traffic intensity increases there is only a gradual increase for the delay times of broadcast packets using flooding. This is due to the priority scheme created by separating the different packet types into two queues.

To establish minimum hop paths we used the routing protocol described in [12]. We observed that based on the order in which the routes are learned by the different network nodes, the shortest paths from a single source to all destination may not constitute a tree. Instead a node might receive the same broadcast packet twice from different neighbors with

one being destined for itself and the other for more distant nodes. The disadvantage of this situation is that unnecessary broadcast packets might be transmitted that may increase the delay time of other network packets. The advantage is that on occasion more routes are used. This serves as a form of load balancing among several possible routes of equal length, thereby decreasing congestion at some nodes that may in turn decrease the delay experienced by some packets.

Unlike wire-based networks where multidestination routing outperforms flooding, in a radio network using TDMA, controlled flooding gives lower average delay than multidestination routing. Part of the reason for this was the use of a separate queue for broadcast packets. However, controlled flooding also uses all possible routes. Thus if congestion is experienced at some points in the network, the broadcast packet may be able to bypass the congested nodes via other less used routes.

Figure 11 show the affect of broadcast traffic on single destination packets when node allocation is used with multidestination routing. As expected, the higher the broadcast rate the greater the affect on single destination packets. Figure 12 show the results when controlled flooding is used. Except at higher load levels, there is minimal difference in the delay as the number of broadcast packets increases. Here the two separate queues prevent broadcast messages from influencing single destination packets. Similar results are observed when link allocation is used.

The final four I ,gures 13 through 16 compare the delay times for broadcast packets as the network density changes. Figures 13 and 14 show the average system time for broadcast packets using link allocation and node allocation in networks employing multidestination routing. As the network density increases the average delay experienced by a broadcast packet increases. The increase in delays are proportional to the increase in cycle lengths observed in Table 1.

Figures 15 and 16 give results when controlled flooding is used in the networks to route broadcast packets. For link allocation the networks with a medium density offer better performance than those with a lower and higher density. Several interacting factors contribute to this finding. The controlled flooding protocol utilizes all possible routes. This means that nodes on less busy routes will expedite the delivery of the broadcast packet by bypassing congested nodes via other available routes. In addition, the diameter of the

medium density network is less than that of a sparse network. Therefore in a medium density network, fewer hops are required for a packet to reach all nodes. In sparse networks, there are fewer routes and the diameter is greater. Thus a broadcast packet is forced to traverse more hops and use congested nodes. Using this same reasoning we might expect dense networks to offer even better performance. Here, however, the transmission cycle length is on the average about twice that of a medium density network, 35 vs 16.33. In addition, because of the increased connectivity there is a higher probability that a node will handle more broadcast packets at once, resulting in more congestion and longer queues. Thus any savings obtained by using alternate routes and shorter distances are lost because of the longer cycle length and increased probability of waiting in queues.

For node allocation using controlled flooding, we see that initially the medium and dense networks offer better performance than the sparse network for broadcast packets. Again the fact that all routes are used for broadcast packets, facilitates their delivery. At higher load levels the highly interconnected networks cause more congestion, and that coupled with the longer transmission cycles cause higher delay times in the more dense networks than in the sparse network.
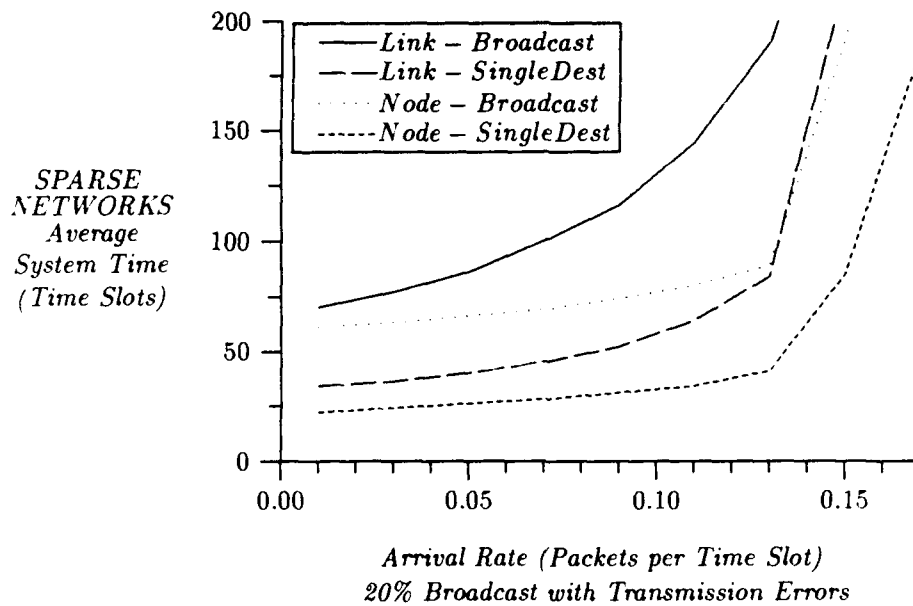
Arrival Rate (Packets per Time Slot)
20% Broadcast with Transmission Errors

Figure 7: LINK vs NODE: Multidestination Routing

Arrival Rate (Packets per Time Slot)
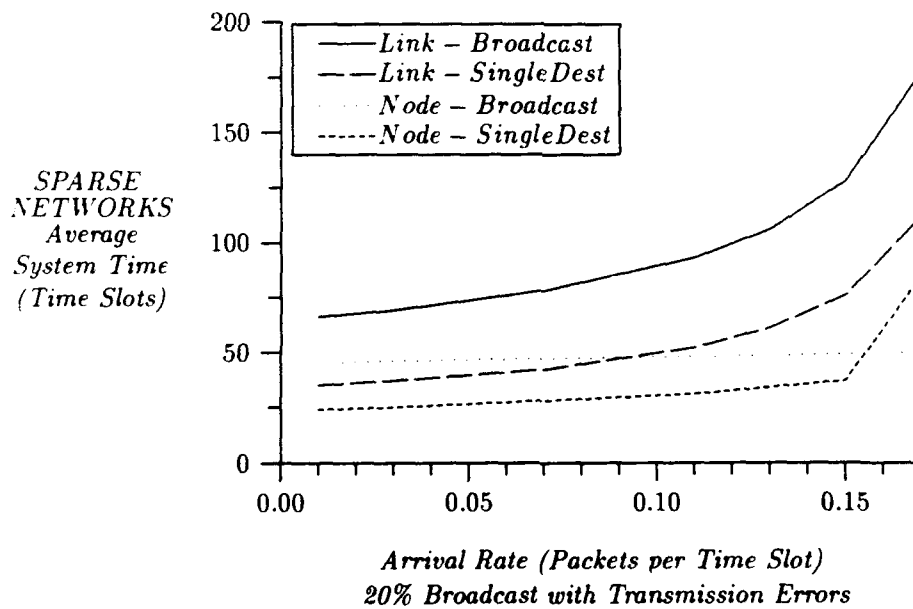*20% Broadcast with Transmission Errors*

Figure 8: LINK vs NODE: Controlled Flooding
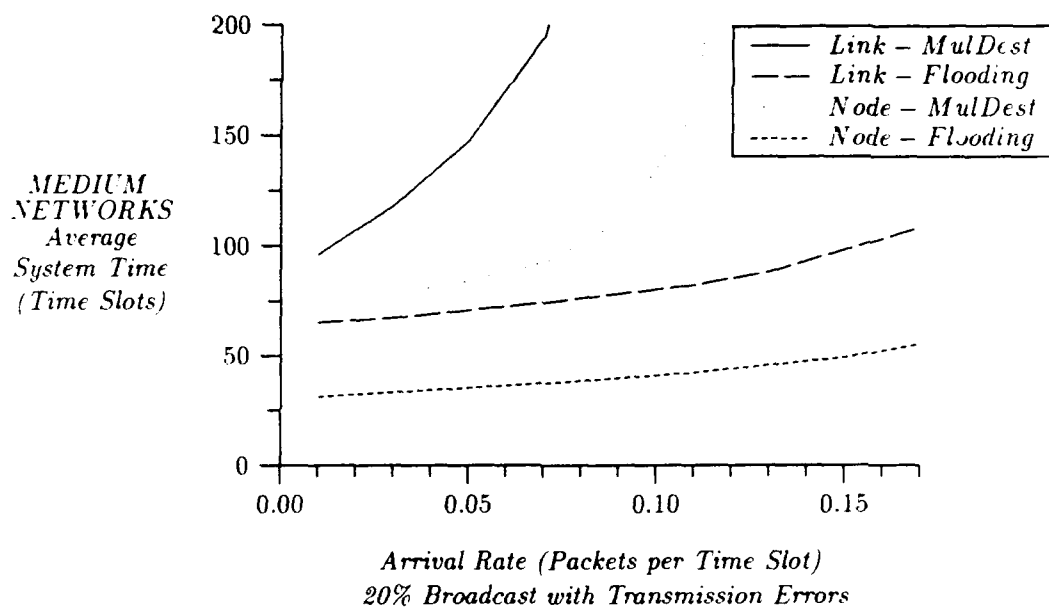
Figure 9: MULTIDESTINATION vs FLOODING: Broadcast Packets
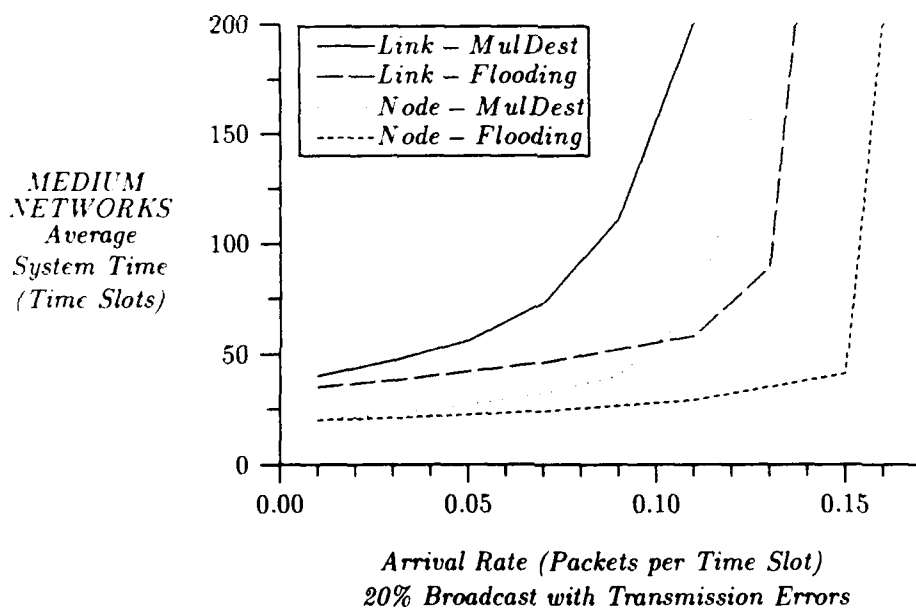
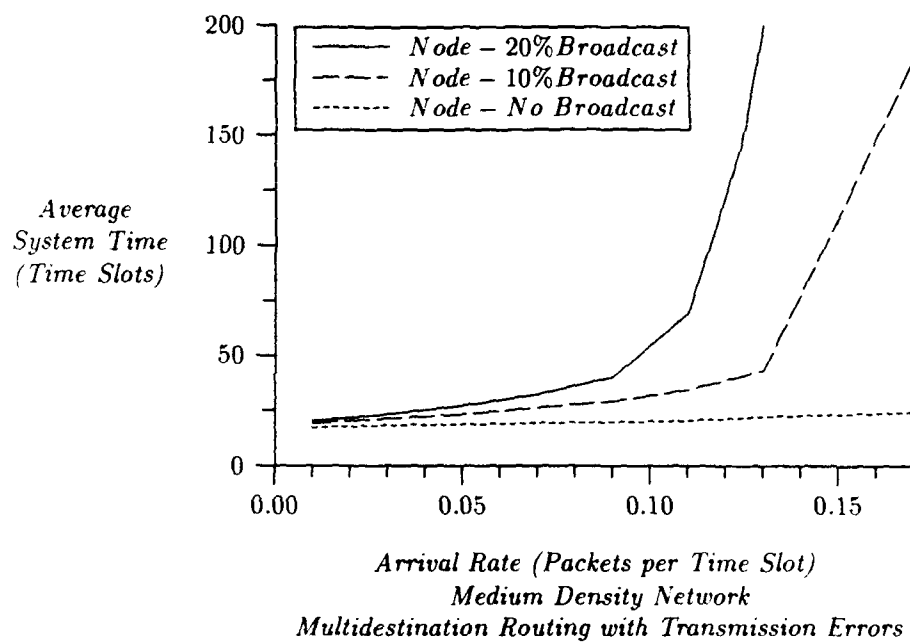Figure 10: MULTIDESTINATION vs FLOODING: Single Destination Packets

Average
System Time
(Time Slots)

Arrival Rate (Packets per Time Slot)
Medium Density Network
Multidestination Routing with Transmission Errors

Figure 11: Single Destination Packets: NODE Allocation

Average
System Time
(Time Slots)

Arrival Rate (Packets per Time Slot)
Medium Density Network
Controlled Flooding with Transmission Errors
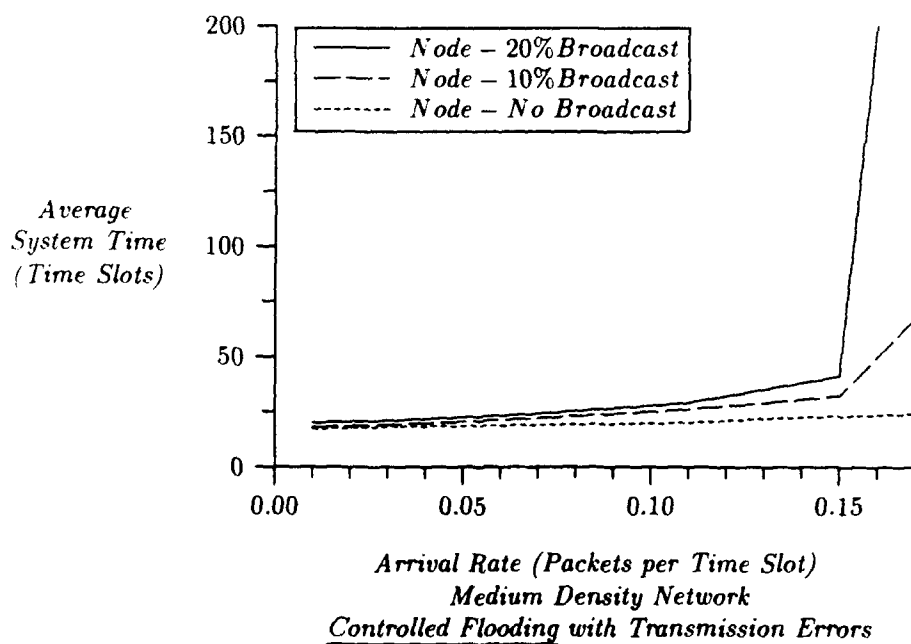
Figure 12: Single Destination Packets: NODE Allocation

Average
System Time
(Time Slots)

Arrival Rate (Packets per Time Slot)
20% Broadcast with Transmission Errors
LINK Allocation - Broadcast Packets
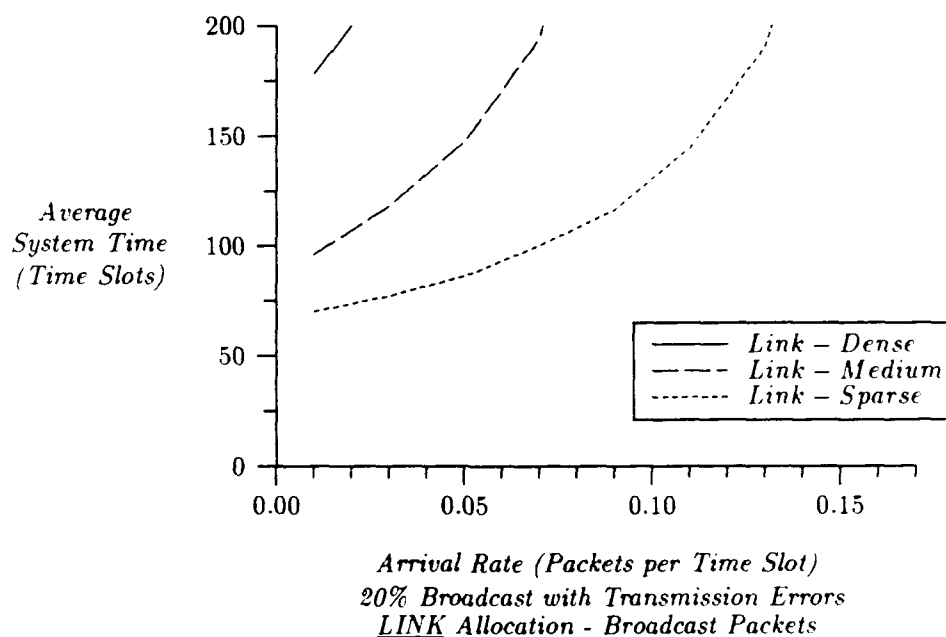
Figure 13: SPARSE vs MEDIUM vs DENSE: Multidestination Routing

Average
System Time
(Time Slots)

Arrival Rate (Packets per Time Slot)
20% Broadcast with Transmission Errors
NODE Allocation - Broadcast Packets
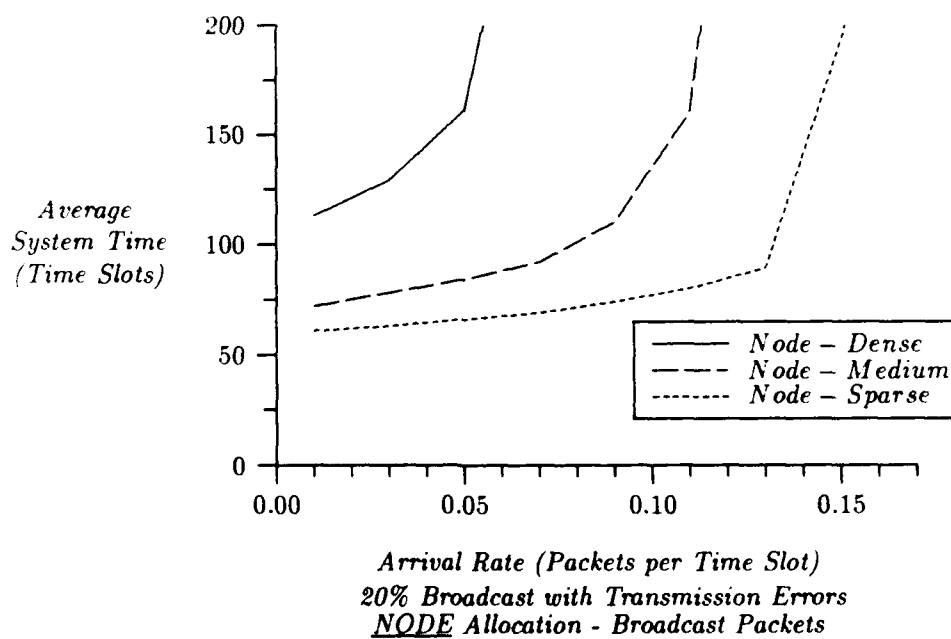
Figure 14: SPARSE vs MEDIUM vs DENSE: Multidestination Routing

Arrival Rate (Packets per Time Slot)
20% Broadcast with Transmission Errors
LINK Allocation - Broadcast Packets
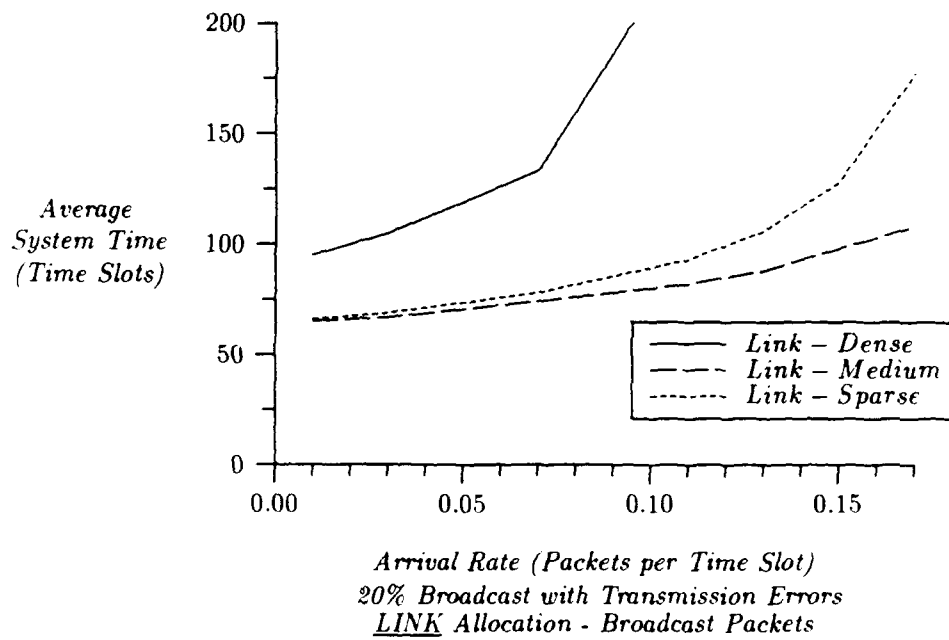
Figure 15: SPARSE vs MEDIUM vs DENSE: Controlled Flooding

Arrival Rate (Packets per Time Slot)
20% Broadcast with Transmission Errors
NODE Allocation - Broadcast Packets
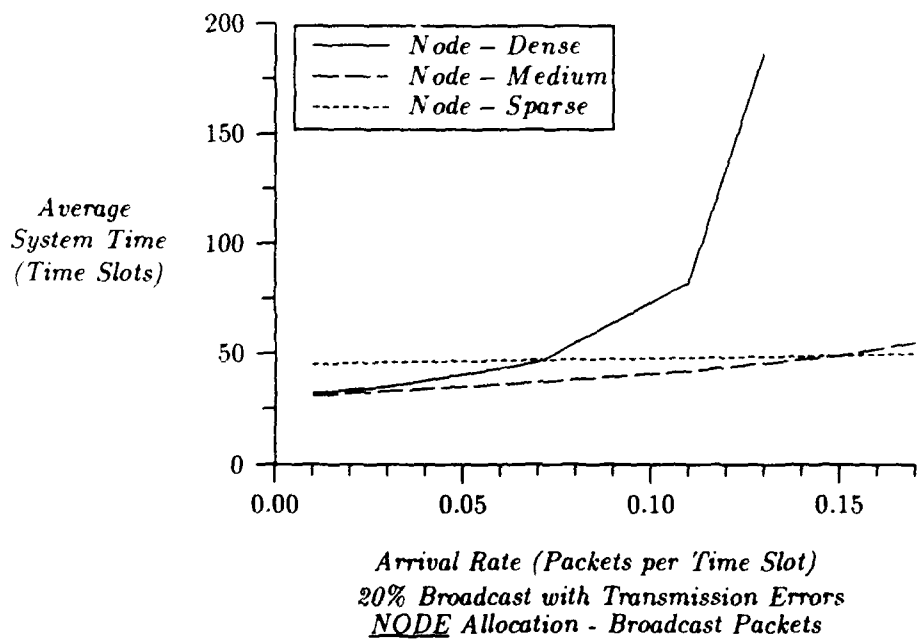
Figure 16: SPARSE vs MEDIUM vs DENSE: Controlled Flooding

5.4   An Exception

Although our conclusion is that node allocation provides better delay performance in general, one can always find a situation where link allocation yields lower delays. Consider for example Tables 3 and 4 that show, for the six randomly generated sparse networks, the delay times for both broadcast and single destination packets using multidestination routing with 10% broadcast traffic. For Network 5, at low traffic levels, the link allocation scheme gives better delay performance for broadcast packets than did the node allocation strategy. The topology for this network is such that four nodes are connected in series to form a "bridge" between the remaining nodes with 12 nodes grouped together on one side and 14 on the other. (See Figure 17.) Also the difference between cycle lengths for node and link allocation in this network is less than the average. Node allocation had a cycle length of 5 time slots while link allocation had a length of 8 slots (see Table 1). This fact tends to favor *single* destination packets using the link allocation protocol (See Section 2).

We observe that at a low load level broadcast packets have lower delay times for the link allocation scheme than the node allocation scheme. The opposite, however, is true for single destination packets. Two factors contribute to these results. First, the nodes forming the bridge must handle traffic in both directions. When the traffic load is light, queues are more likely to form in these nodes when the node allocation scheme is used (a single queue for both directions vs. a separate queue for each direction in link allocation). Second, the difference between the two cycle lengths for this network is small. Thus any packet traversing the bridge will have longer delay times in the node allocation scheme. *All* broadcast packets must be routed across the bridge. Since they are all affected, the average system time for broadcast packets in light loads is higher in the node allocation scheme.

As the traffic load increases, queues will develop not only at the nodes forming the bridge, but in all other network nodes. Queues in the network using link allocation affect delay more adversely because of the longer cycle time. Thus at higher load levels, the advantage shifts to node allocation, and the delay across the bridge becomes less of a factor. This explains why at higher load levels node allocation offers better delay performance for broadcast packets than link allocation.

Single destination traffic traversing the bridge is also subject to the same delay as broadcast packets, but not every single destination packet is routed over this portion of
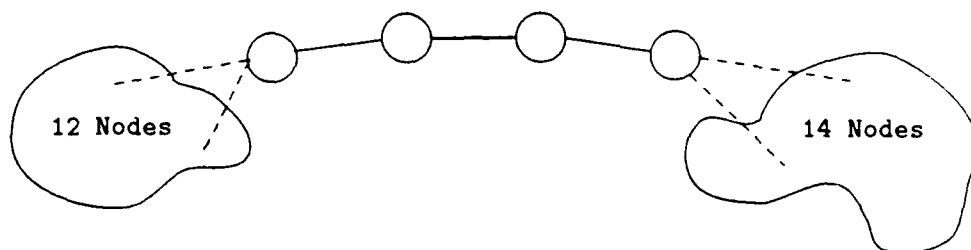
Figure 17: Network 5

the network. Thus the shorter transmission cycle of the node allocation scheme keeps the *average* delay for single destination traffic lower than that of the link allocation scheme.

6 Conclusion

In this paper we addressed the issue of which TDMA allocation scheme - link or node. offers better delay performance in a packet radio network. We considered those TDMA schemes that allocate one slot per node per cycle for node allocation and one slot per directed link per cycle for link allocation. We used a detailed simulation to evaluate the average delay times that are experienced by both single destination and broadcast packets. To route broadcast packets we used a multidestination routing protocol and a controlled flooding protocol. As pointed out in Tables 3 and 4, given a specific network topology under some load conditions, link allocation may offer better performance. However, in all cases the delay times averaged across the randomly generated networks are lower for node allocation.

One of the arguments for using link allocation in packet radio networks is that protocols applicable to wire-based networks can be easily adapted to operate in the radio environment. However, we conclude that using link allocation is not really advantageous. Not only do single destination packets do better using a node allocation strategy, but broadcast packets using either multidestination routing or controlled flooding protocol also experience lower average delays. The major factor contributing to the better performance in the node allocation scheme is its shorter transmission cycle length.

Arvl Rate	Net 1		Net 2		Net 3		Net 4		Net 5		Net 6	
	Bdct	SD	Bdct	SD	Bdct	SD	Bdct	SD	Bdct	SD	Bdct	SD
.01	79.2	24.4	58.2	23.5	44.9	17.3	56.2	23.1	71.7	23.8	53.9	20.9
.03	80.8	26.1	61.0	25.1	45.3	17.9	57.7	23.9	73.4	25.2	56.3	21.8
.05	83.8	28.3	62.6	26.7	47.1	18.6	59.3	25.3	75.1	26.4	57.1	22.8
.07	87.7	30.0	66.9	28.2	48.1	19.4	61.0	26.7	79.0	28.0	61.4	24.9
.09	91.7	32.4	68.9	30.1	49.2	20.0	63.2	27.9	82.0	30.3	62.7	26.2
.11	94.5	35.2	73.0	32.6	50.8	20.7	65.7	29.0	85.7	33.6	65.2	28.2
.13	102.7	41.0	78.6	36.6	51.8	21.7	69.4	31.5	91.1	37.0	69.7	30.~
.15	144.8	69.2	88.7	44.5	55.0	22.9	71.4	33.4	106.7	44.3	73.5	34.~

Table 3: Node Allocation - 10% Broadcast Packets, Sparse Networks, With Transmission Errors

Arvl Rate	Net 1		Net 2		Net 3		Net 4		Net 5		Net 6	
	Bdct	SD	Bdct	SD	Bdct	SD	Bdct	SD	Bdct	SD	Bdct	SD
.01	88.6	41.3	60.9	29.8	71.4	32.5	75.4	36.5	63.2	28.4	57.2	27.4
.03	96.5	42.7	65.2	32.1	75.6	35.0	81.8	39.2	66.9	30.9	62.6	29.2
.05	105.9	49.4	71.1	34.4	81.7	39.5	87.7	42.5	70.6	33.3	67.7	32.9
.07	117.9	55.4	77.4	37.6	92.3	41.2	95.6	46.2	79.1	36.7	73.8	35.3
.09	138.2	64.6	84.6	41.9	103.8	45.1	106.2	51.4	89.2	40.6	78.8	38.2
.11	167.3	80.5	95.6	47.4	116.8	50.5	120.0	58.6	98.6	46.2	88.4	42.0
.13	232.8	108.1	113.4	54.9	136.4	56.6	141.9	69.5	118.5	53.2	101.6	47.3
.15	355.6	182.0	139.4	66.6	156.3	65.6	174.1	86.6	141.9	64.8	118.6	55.0

Table 4: Link Allocation - 10% Broadcast Packets, Sparse Networks, With Transmission Errors

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